

Practical aspects of medical application of FFAG (in case of PAMELA)

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Introduction

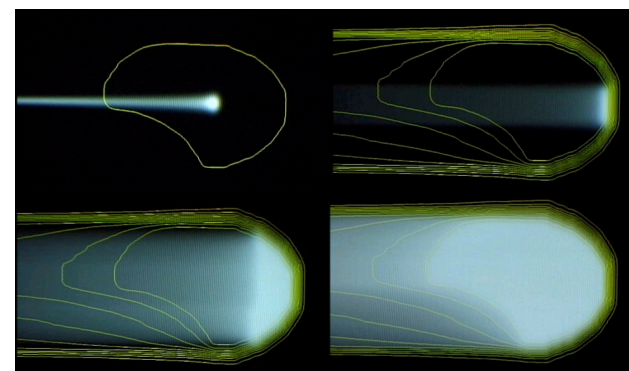
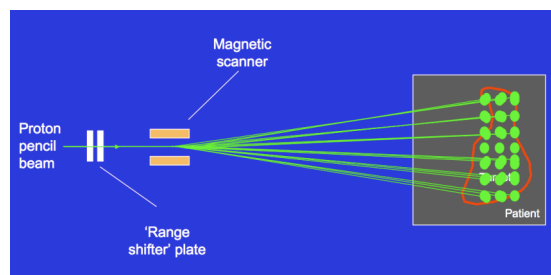
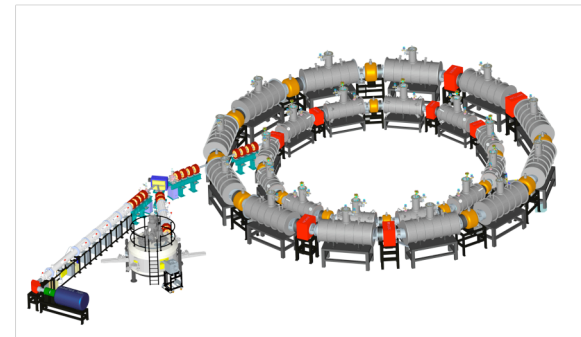
**PAMELA is a design study of particle therapy facility using ns-FFAG
(spot scanning is the treatment model)
(Injector \Rightarrow cyclotron : proton, RFQ+linac : carbon)**

Practical aspects including treatment scenario needs to be taken into account in the design stage.

\Rightarrow Our target is human body, not production target

Things to be considered as a treatment system are

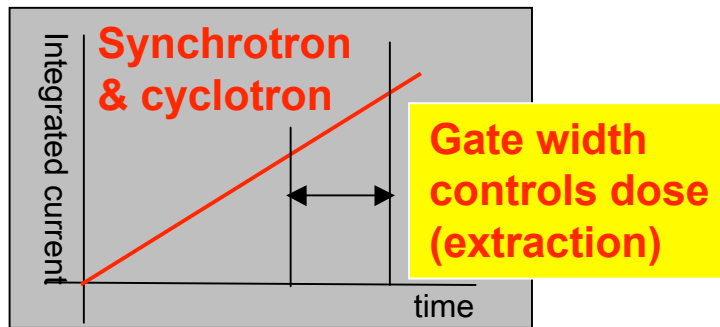
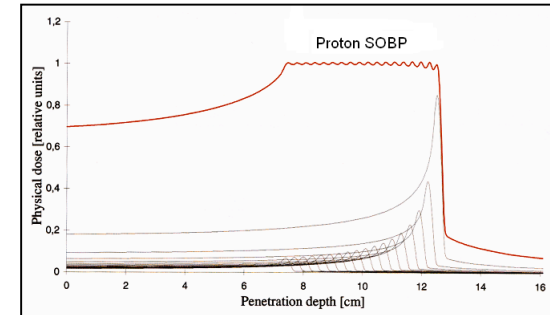
- (1) Intensity control (\Leftarrow QA)**
- (2) Beam shape & position control (\Leftarrow QA)**
- (3) Scanning system configuration**



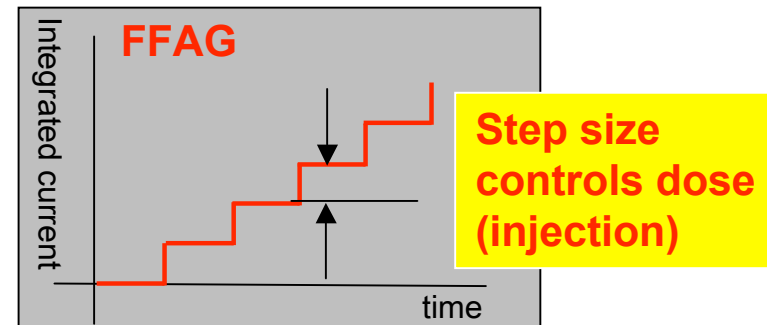
Dose control in a pulsed accelerator

To form a uniform dose field in spot scanning, beam intensity needs to be modulated depth-wise

⇒ **IMPT (Intensity Modulated Particle Therapy)**



“Analog IM”



“Digital IM”

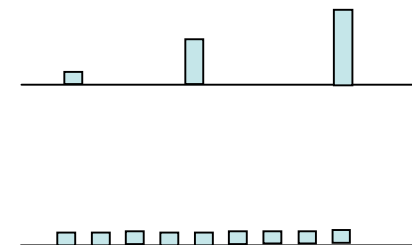
With pulsed beam of FFAG, to realize intensity modulation

(1) Dynamic modulation of injector beam intensity

complicated system, but low repetition rate

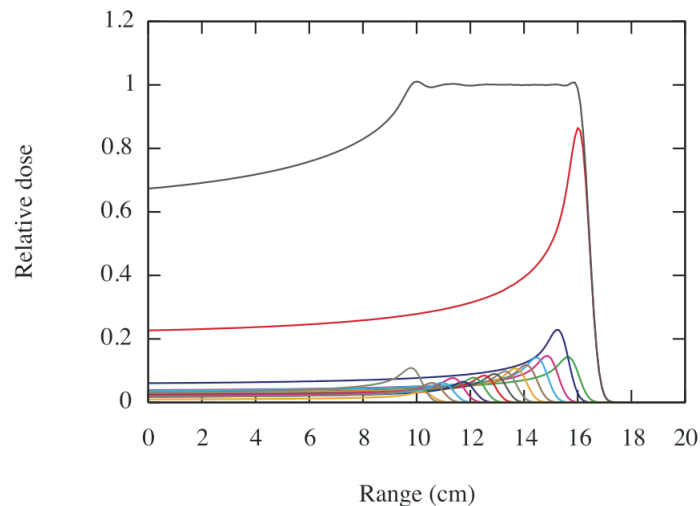
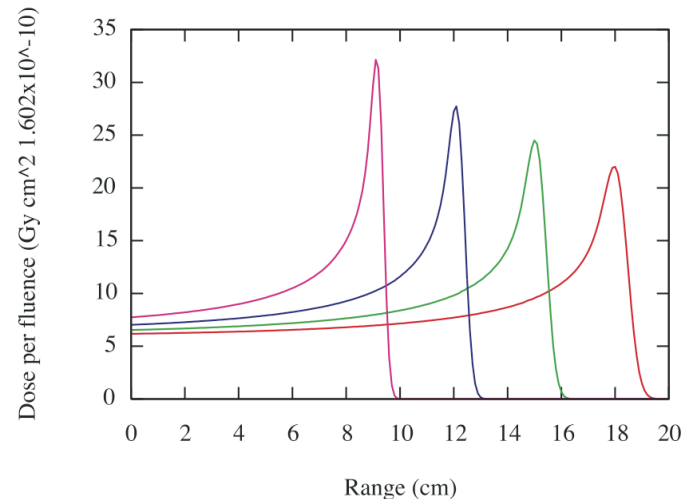
(2) multi-beam painting with small bunch intensity

simple system, but high repetition rate



In PAMELA, option (2) is adopted

Intensity requirement



Formation of SOBP with analytical Bragg peak model

- To deliver a dose over 1 liter target volume (10x10x10cm) within 1min, required intensity is 0.2nA/GyE (for multi-bunch painting, **pulse intensity : $\sim 10^6$ proton/GyE :1kHz**)

(Further reduction is expected in case of patch field irradiation: four-field superposition is expected in maximum)

- For the widest SOBP, **8 beamlet/voxel** \Rightarrow if 1kHz repetition rate is achieved, more than 100 voxel/sec can be scanned

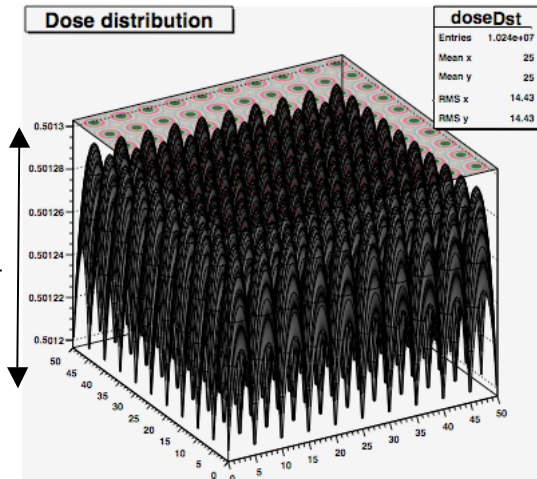
Need confirmation using treatment planning system

Crucial parameter of a pulsed accelerator for particle therapy is repetition rate

Horizontal scanning with beam positioning error

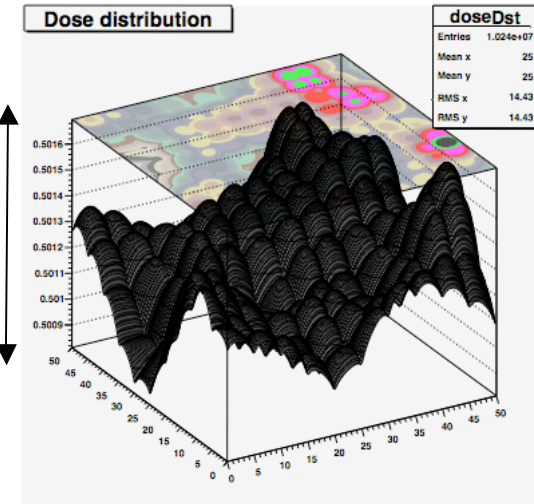
Position error
: 0.0mm (σ)

$$\Delta D/D \sim 1 \times 10^{-4}$$



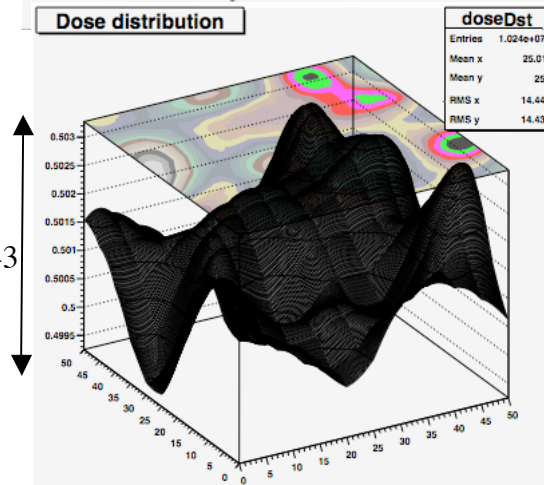
Position error
: 0.001mm (σ)

$$\Delta D/D \sim 7 \times 10^{-4}$$



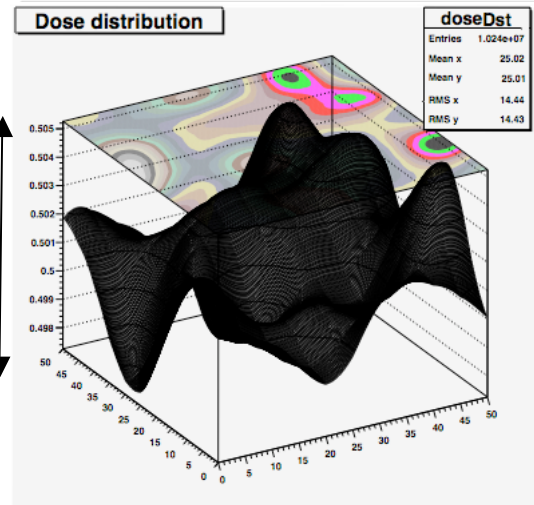
Position error
: 0.005mm (σ)

$$\Delta D/D \sim 3 \times 10^{-3}$$



Position error
: 0.01mm (σ)

$$\Delta D/D \sim 7 \times 10^{-3}$$



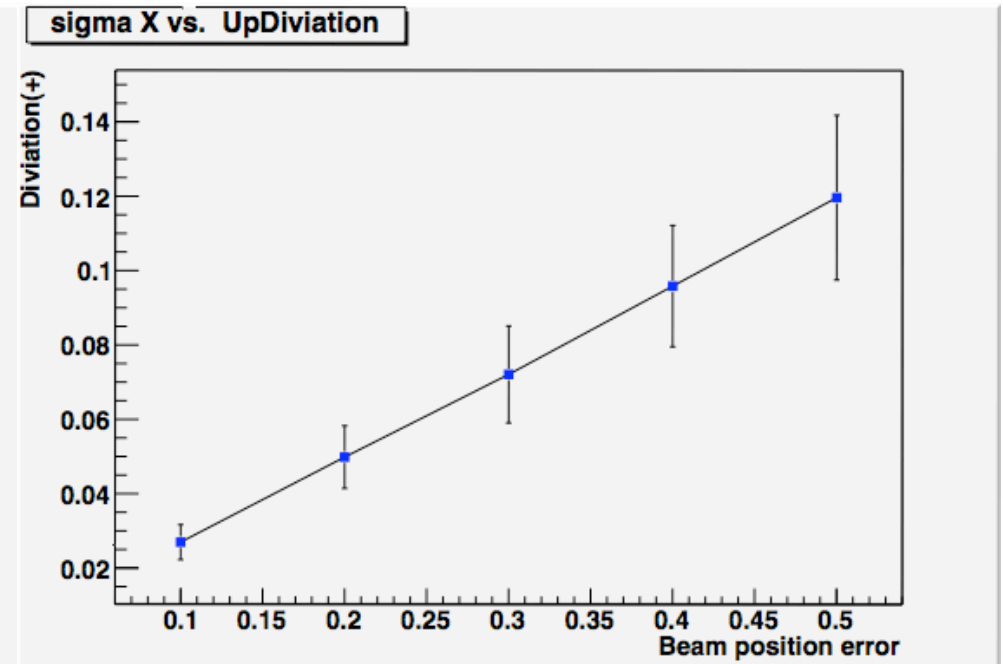
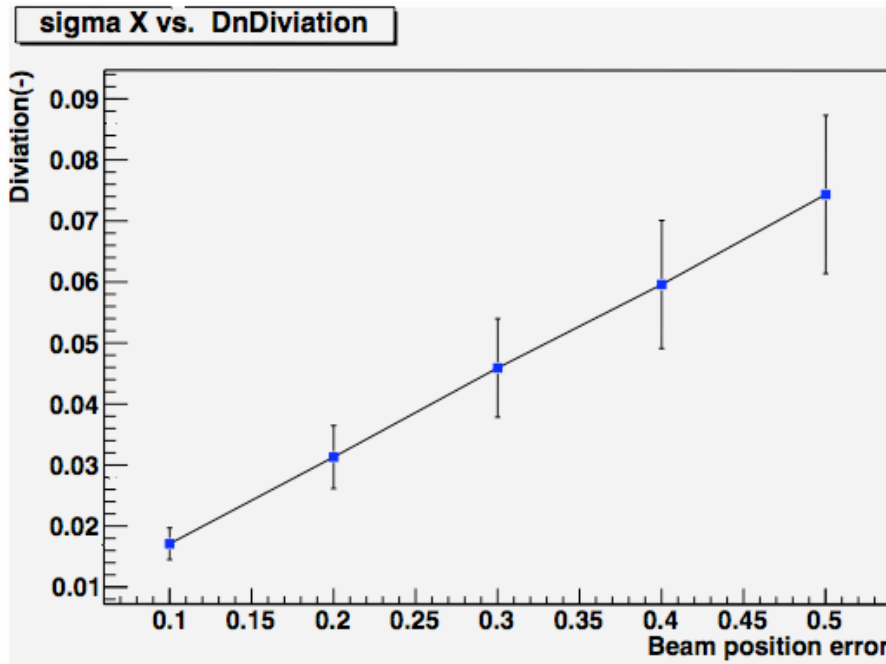
* Grid size : 5mm, Beam size : 5mm (σ)

With a finite beam positioning error, dose uniformity is drastically deteriorated

Deviation from average dose

(1) : $(D_{\min} - D_{avr}) / D_{avr}$: Underdose

(2) : $(D_{\max} - D_{avr}) / D_{avr}$: Overdose

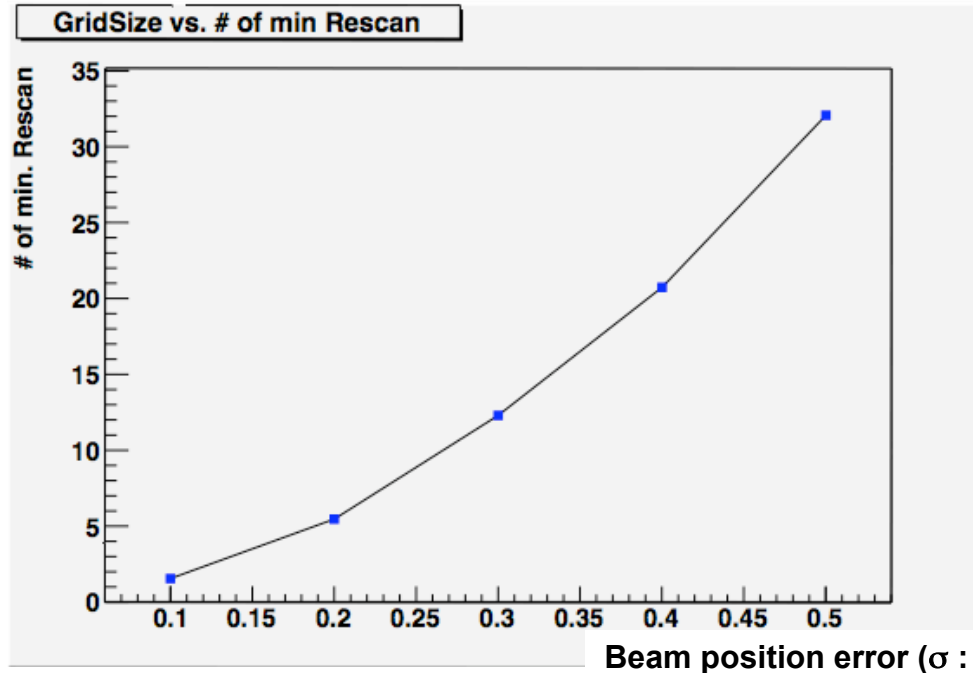


- Grid size : 5mm,
- * Beam size : 5mm (σ)
- * Number of statistics: 100

Deterioration of uniformity is proportional to positioning error

Rescanning

Uniformity improves proportional to $\sqrt{N_{rescan}}$



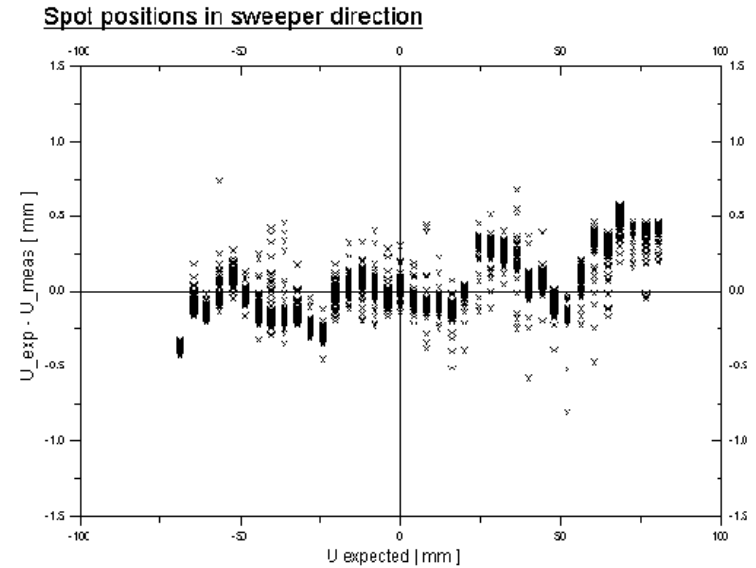
- * Grid size : 5mm,
- * Beam size : 5mm (σ)

Number of rescanning required to achieve uniformity of 2% over the region
 (the limit is set at 3σ from the average underdose to ensure 99% case can satisfy the criterion of uniformity)

Rescanning of several times might be required in future.
Precision of spot position is crucially important for treatment efficiency
⇒Orbit correction is essentially important in FFAG

Beam requirement

- With existing technology, beam position reproducibility of 0.2mm can be achieved (PSI : cyclotron)
 - Present technologies of diagnostics (ex CT) can measure 3D internal structure with a precision of 0.2mm.
- ⇒ Precision of 0.2mm(σ) is a reasonable target. (but not so easy number to realize)



@PSI Gantry 1

- Even with the precision of 0.2mm, rescanning ~ 5 would be needed to satisfy the requirement of tolerance (multi-bunch painting is in itself a sort of rescanning. necessity of rescanning might be eliminated if beam precision < 0.2 mm)
- ⇐ With rescanning, the advantage of direct intensity modulation against multi-bunch painting is almost diminished)

Overall requirement

Intensity

- In real treatment, maximum 4 fields can be superposed.
- Single dose : proton : 1~7 GyE, carbon :2~12GyE
⇒ Intensity modulation of (at least) more than factor of 30 would be required with a precision of 2%
- Proton:0.2nA/GyE ⇒ 0.05nA~1.4 nA

**Direct intensity modulation must be anyhow implemented.
(DIM with chopper would not be sufficient as long as
employing cyclotron as the injector. Real system would be a
hybrid of IM at ion source and chopper)**

Beam Position reproducibility

- 0.2mm(σ) at target voxel \Leftarrow **Beam steering system is indispensable
in the extraction beam line (in FFAG, from ion source to patient is
one beam line)**

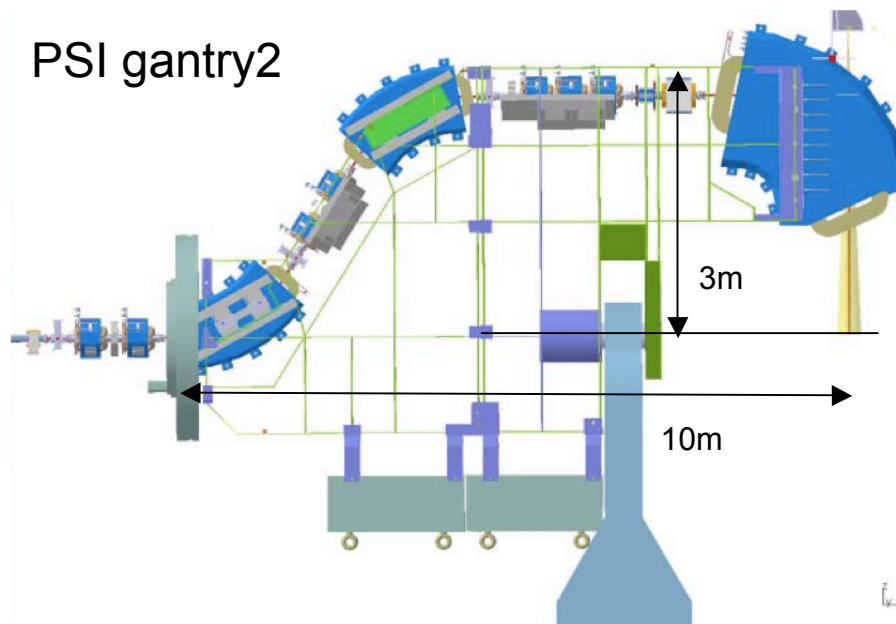
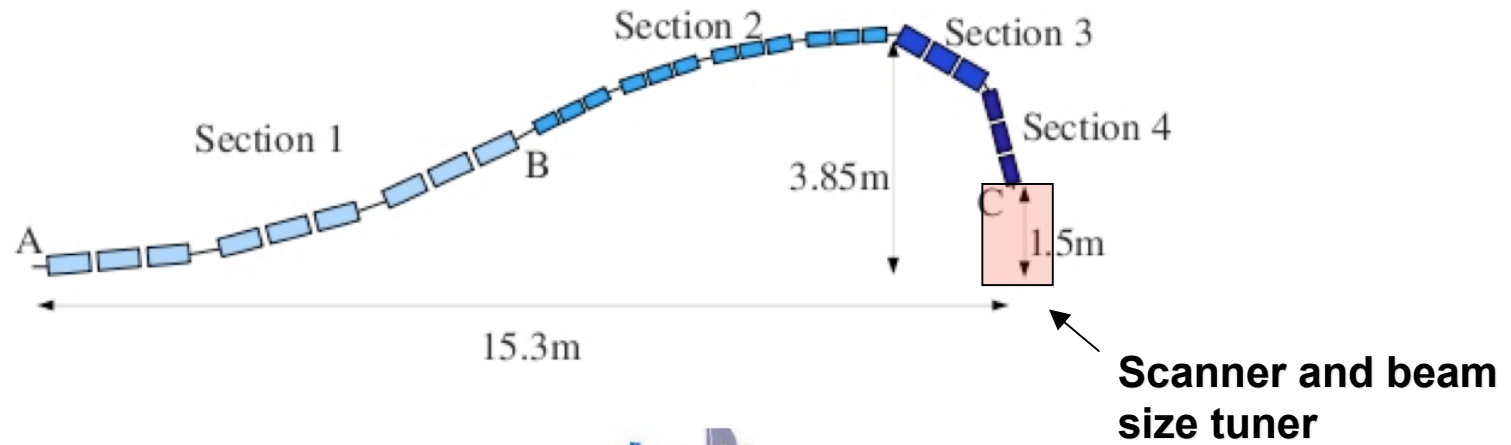
Beam size

- 4mm~10mm(FWHM) \Leftarrow Beam size might be needed to vary during a treatment

Scanning system of PAMELA

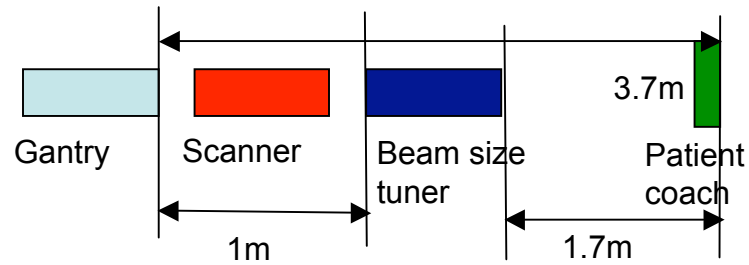
- Two functions of scanning system
 - (1) to deliver beam to the point specified by treatment plan**
 - (2) to shape the beam spot specified by treatment plan**
- ** It is desirable to decouple function (1) and (2)**
- Dose field requirements
 - (1) Field size : $\pm 10\text{cm} \times \pm 10\text{cm}$ @patient
 - (2) spot size : $4\text{mm} \times 4\text{mm} \sim 10\text{mm} \times 10\text{mm}$ (FWHM) @ patient
- Beam divergence: Existing working scanning system realizes parallel beam (max divergence < 1 degree)
 - One downstream scanner in US (not working yet)
- In PAMELA, beam transport and gantry employ FFAG optics

FFAG gantry

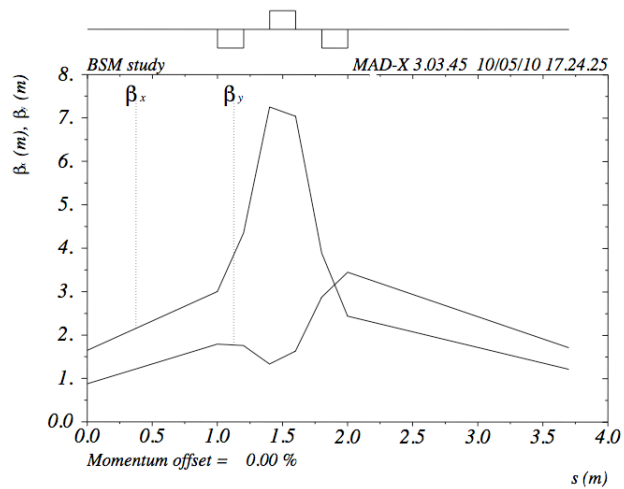


To compete with existing gantry size-wise
radius <5m, length <10m

Upstream scanning

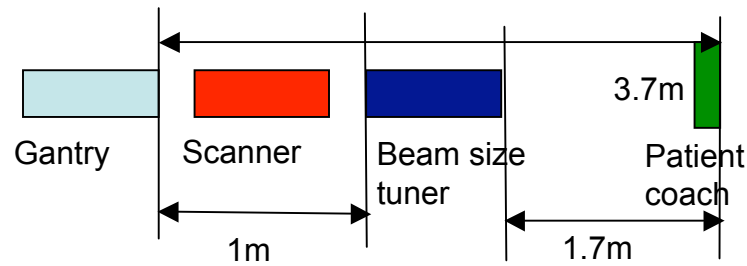


- Smaller divergence
- Large aperture at BST
- Complicated optics /system (coupled system)

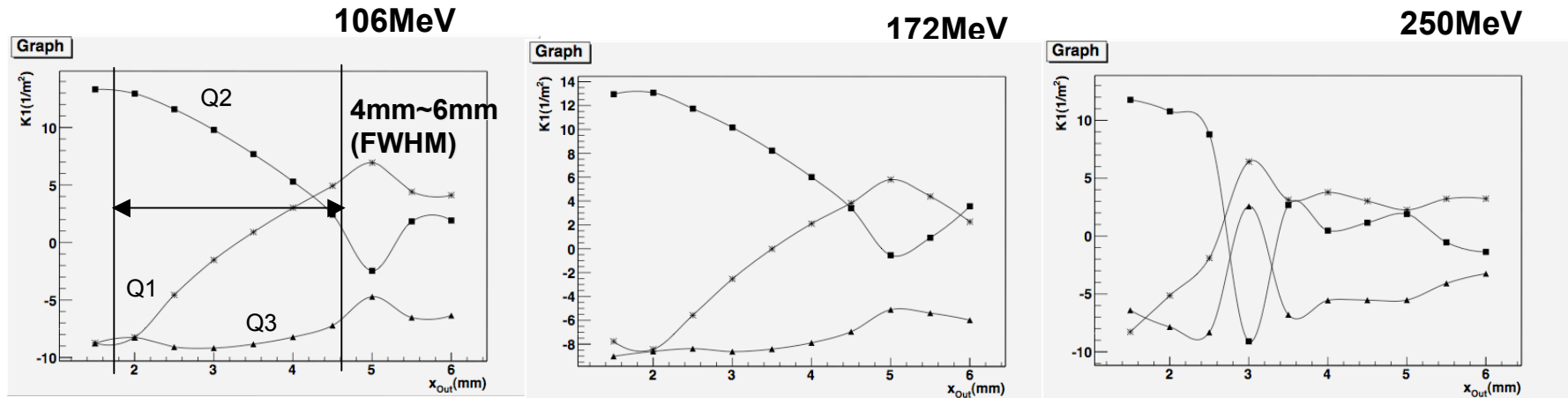


X: 4mm×4mm

Upstream scanning

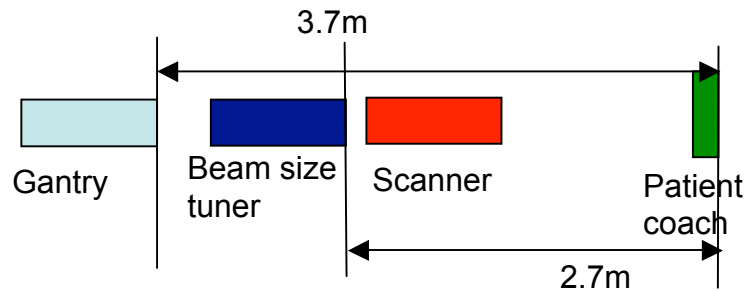


- Smaller divergence
- Large aperture at BST
- Complicated optics /system (coupled system)



- Maximum field gradient :28T/m
- Problem is orbit correction due to off-centered orbit in quadrupole.
 - Max Divergence is ~35mrad. \Rightarrow Max deviation from the magnet centre ~4cm
 - $28\text{T/m} \cdot 0.04\text{m} = 1.12\text{T} (@250\text{MeV})$, \Rightarrow Max bending power by Q:0.2.24T.m
 - Max bending power @scanner ~0.035rad*2.3T.m~ 0.08T.m
 - Scanner and beam size tuner are tightly coupled optics-wise
- Another problem is large aperture of beam size tuner (> 50mm bore radius)
 - ex 50mm bore, 28T/m quadrupole \Rightarrow ~27000A.T

Downstream scanning

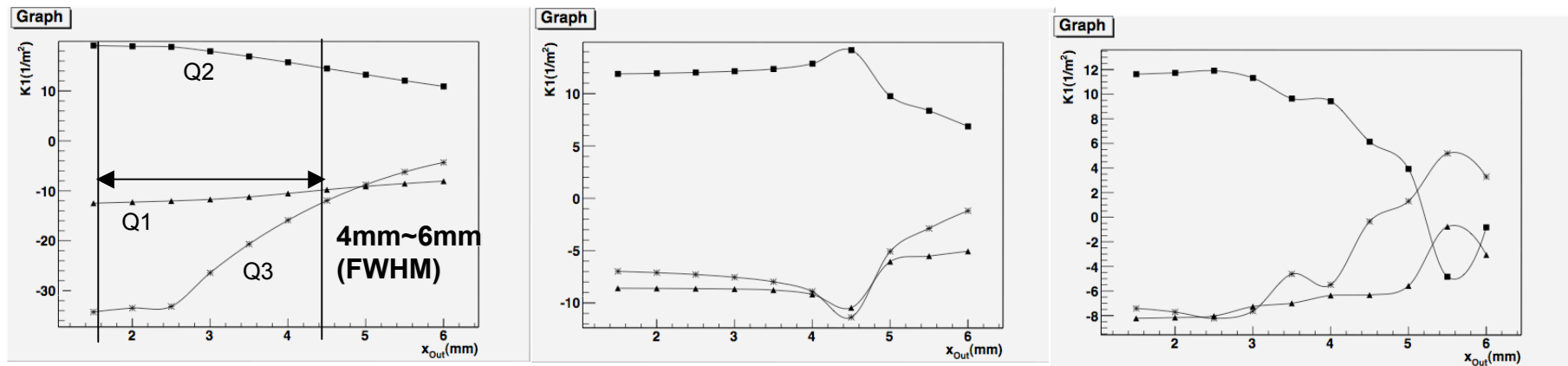


- Larger divergence
- Smaller at BST
- Simple optics /system (decoupled system)

106MeV

172MeV

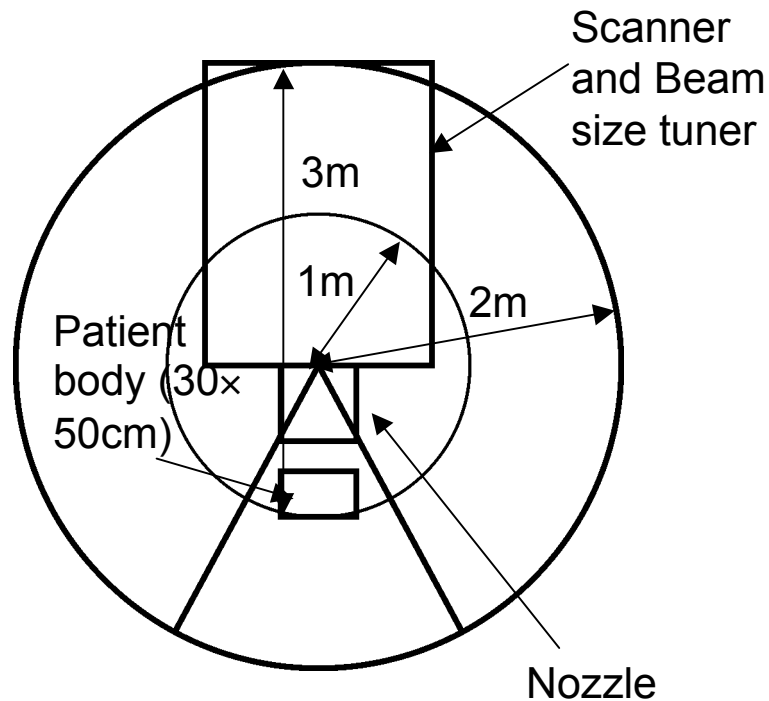
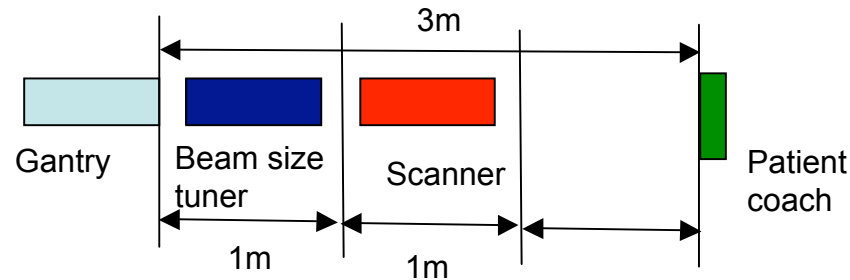
250MeV



Maximum field gradient :50T/m (3 cm would be sufficient \Leftarrow beam size<1cm)

Large beam divergence (max 50mrad)

Geometrical consideration of FFAG gantry



- Required space
 - 2m : Scanning system
 - 0.5m : nozzle
 - 0.5m : patient space
- ⇒ Space~3m should be spared
- Potential problem is long distance of coach movement (treatment planning, positioning accuracy)
 - H:>2m, V:>1m
 - ⇐ No existing system in the world moves patient couch over such a long distance

Possible options

1. Full FFAG option (FFAG transport + FFAG gantry)

Exocentric gantry is at the moment only possible option
(isocentric gantry becomes too large)

Large beam divergence

Switching section and steering system are problem

2. Conventional gantry option

Existing system is fully employed (minimum development risk)

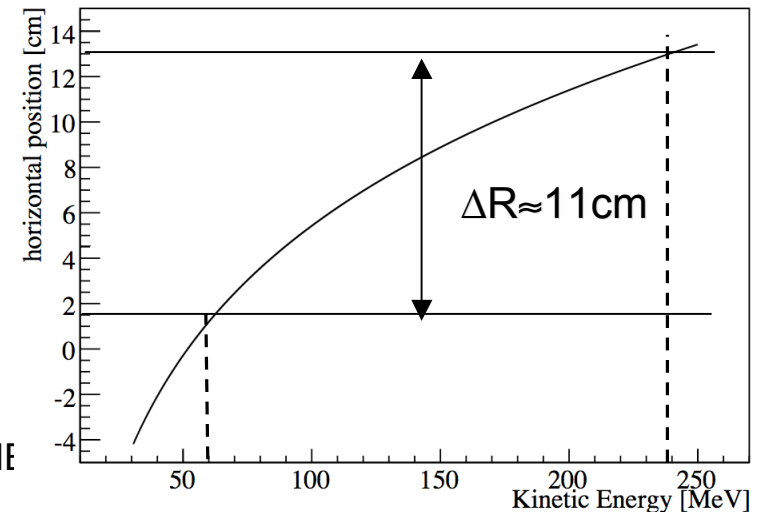
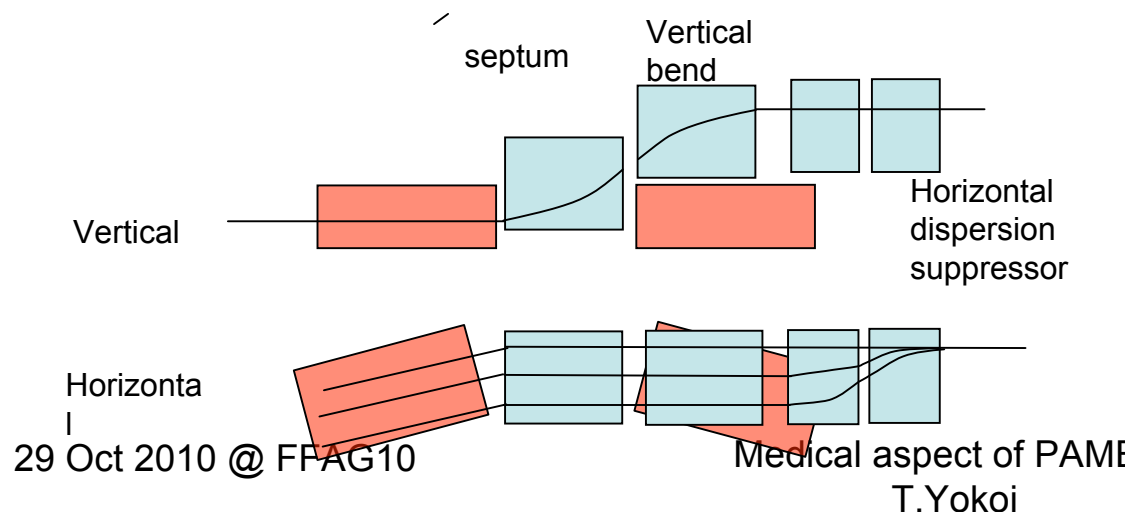
3. Hybrid option(FFAG transport + conventional gantry)

Switching section (and steering system) are problem

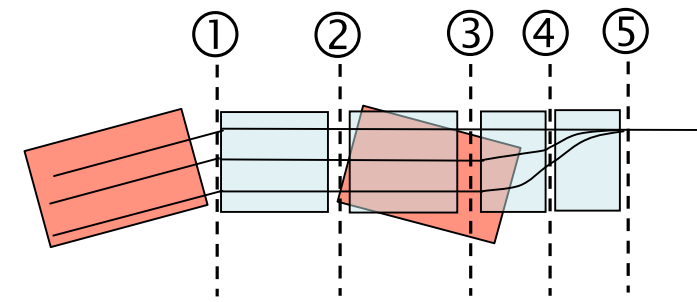
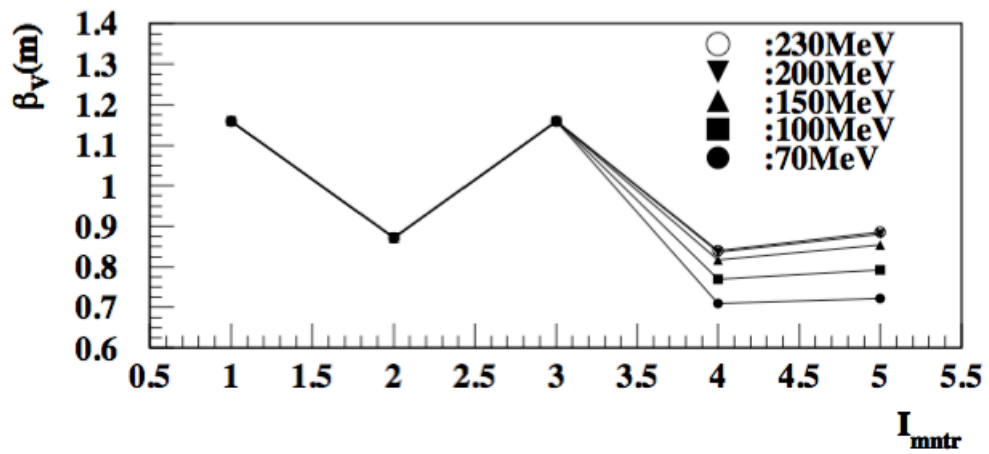
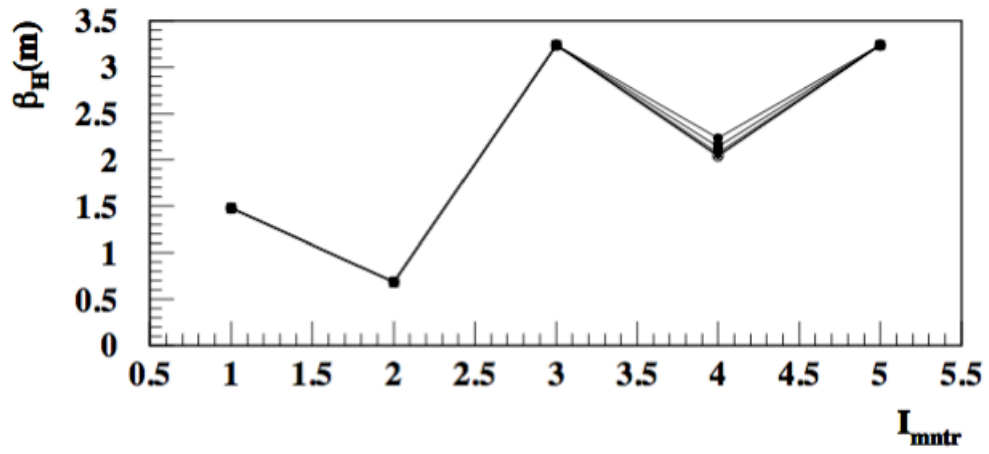
At the moment, option 1 and 2 are listed as candidates. (FFAG option still needs time to mature)

Connection to Transport line

- In vertical beam extraction, two vertical bending magnet is required.
- In PAMELA, orbit excursion over the therapeutic energy : ~11cm
⇒ Horizontal dispersion suppressor is required
- ** One approach is FFAG transport with dispersion suppressor
- Taking into account the requirement for a scanning system, FFAG gantry might not be able to go with present scheme (need time to mature)
⇒ “minimum transport configuration”
- The minimum configuration can provides another (backup) option with small development risk using existing beam delivery system.



Optical function @transport



- Optics transport : using transfer matrix
- Optical parameter at entrance : value at the exit of magnet
- Magnet :
 - 1.6T × 70cm, sector (Ver. Ext)
 - 0.8T × 50cm. Rect. (Hor.Match)
- Field change ~1%/ 1 layer.

⇒ **Extraction section can cope with both FFAG transport and conventional options with minimal change of transport. (need revision for combined function septum)**

Summary

- For the application of FFAG to particle therapy, beam control is crucially important (beam position, beam intensity)
- The repetition rate is key issue for pulsed medical machine. (~1kHz)
- Flexible and precise intensity control must be implemented (dynamic range >30, precision <2%)
- LINAC would be more suitable for injector rather than cyclotron
- Newly developed machine should take into account the capacity of rescanning
- Beam position strongly influences to the treatment quality, efficiency
⇒ Orbit correction system in transport line is a requirement
- FFAG transport-gantry still needs time to mature (size, steering, switching etc)
⇒ At the moment, conventional transport + gantry is also considered as an option in PAMELA. Extraction section can cope with both of them)